Drag Mechanisms in Flow Over Rough Topography

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LONG-TERM GOALS

In order to effectively model the coastal ocean, it is essential that we understand how flow over rough topography affects boundary drag. The long-term goal of this work is to develop a physical understanding of oceanic flow along irregular, sloping, coastal topography. By understanding the basic processes of internal wave generation and flow separation we will be able to predict the effects of unresolved bathymetric roughness in numerical simulations.

OBJECTIVES

In this effort we focus on rotating, stratified flow on a slope with a ridge, in both idealized and realistic forms. The slope with a ridge represents a very common geomorphological feature on the coast (as a headland) and on the continental slope. This project is complimentary to work being conducted elsewhere on submarine canyons. We seek to develop observational and numerical methods which allow us to characterize and predict the flow disturbances caused by this form of rough topography. A primary metric is the pressure drag on the ridge, which may be the result of both flow separation and internal wave generation. The pressure drag on topography may easily be much greater than the frictional bottom boundary layer drag. Thus accurate numerical models require that we are able to parameterize the effects of unresolved (sub-grid-scale) bathymetric roughness.

APPROACH

In order to understand the physics of these complex flows, we use a suite of approaches: 3-D numerical simulations, field observations, analytical theory, and lab experiments. These are all focused on the basic configuration of stratified flow past a ridge on a slope. Tidal and rotational effects are included as well. The numerical simulation is done by the MacCready using the Hallberg Isopycnic Model (HIM) and the Region Ocean Modeling System (ROMS). We have completed three years of field work in the Strait of Juan de Fuca, collaborating with Chris Garrett and Richard Dewey at U. Victoria. This data is being analyzed by a graduate student, Wayne Martin. Our current field program (with NSF funding) now focuses on a sharp headland in Puget Sound, Three Tree Point. Dr. Kate Edwards works on data analysis in both locations, as a postdoctoral researcher supported by this grant. Ryan McCabe, a graduate student, works on the Three Tree Point observations, and related, idealized, lab experiments.

WORK COMPLETED

This year MacCready and Dr. Geno Pawlak, the first postdoctoral researcher supported on this grant, completed two papers (MacCready and Pawlak 2001, and Pawlak and MacCready, in press) on our initial numerical simulations and lab experiments. MacCready also wrote two papers (MacCready and Geyer 2001, and MacCready et al., submitted) on a novel way of analyzing isopycnal mass balances in an S-coordinate model. Wayne Martin has analyzed the Juan de Fuca observations for their tidal, boundary layer, and internal wave characteristics. Kate Edwards participated in a cruise of the R/V Thompson at Three Tree Point with Jim Moum of OSU. They took a substantial microstructure dataset there, which Kate is analyzing to calculate both frictional stress and the baroclinic part of form stress across the ridge. Our whole research group participated in a subsequent cruise at Three Tree Point, mainly using GPS drifters and repeated ship-mounted ADCP surveys. Both cruises were supported by MacCready's realistic numerical modeling of the site, allowing us to develop effective sampling strategies.

RESULTS

Pressure drag on stratified flow past a ridge can be due to either internal wave generation, or horizontal flow separation (which forms a headland eddy). Using linear wave theory we have found that the transition from horizontal flow around the ridge to more vertical, wave-like flow over the ridge may be predicted to occur when $U/(LN \sin a) = 1/2$ (faster flow is wavelike) where U is the speed of the along-slope flow, L is the along-slope length of the ridge, N is the buoyancy frequency, and the slope angle is a. Remarkably, this predictive criterion proved useful even for numerical simulations with large ridge height and realistic mixing and boundary layer parameterizations (Fig. 1).
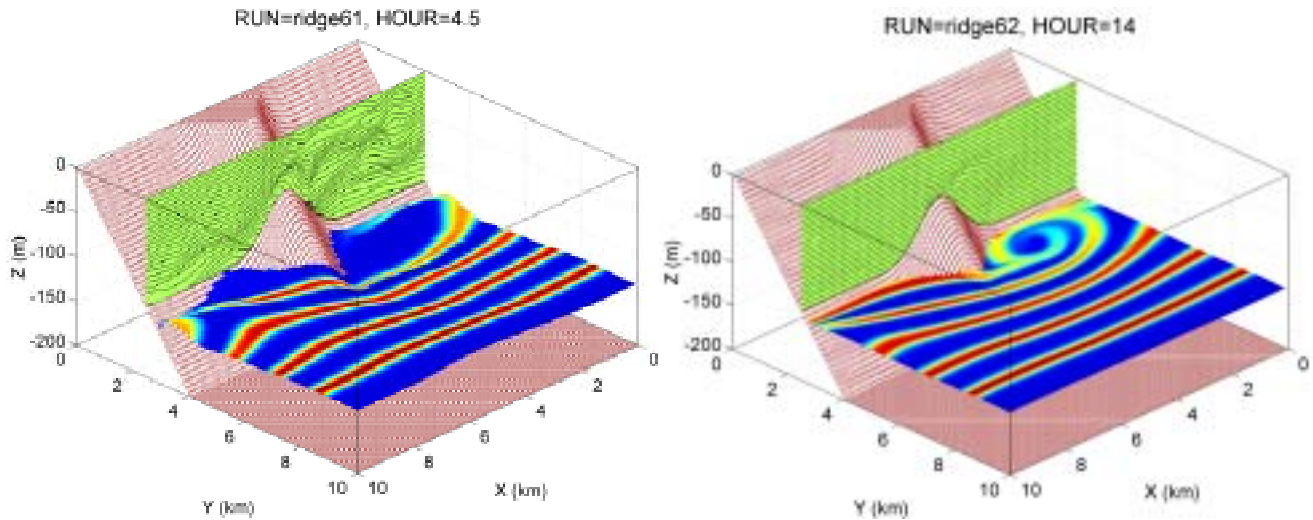

Figure 1. Results from a 40-layer numerical simulation of re-entrant channel flow past a ridge on a slope (slope angle = 1/20). Isopycnal displacements are shown in the vertical plane and tracer stripes are shown on an isopycnal. The run shown in the left panel is forced with a 0.5 m s⁻¹ flow from left to right, and strong lee wave generation is observed, consistent with the analytical predictions. If instead (right panel) we force with a slower flow, 0.125 m s⁻¹, which is below the low-speed cutoff for wave generation, no waves are formed. Instead, a coherent horizontal eddy develops in the wake due to flow separation. The pressure drag coefficient on the ridge is approximately the same in both these cases, despite the different physical mechanisms.

We calculated the pressure drag on the ridge, which may be due to either internal wave generation or horizontal separated flow. In both cases, an extremely simple result emerged. The coefficient of pressure drag, referenced to the projected frontal area of the ridge, was approximately 1 for all large ridges (Fig. 2). In these cases the pressure drag on the ridge was about 5 times greater than the frictional drag.
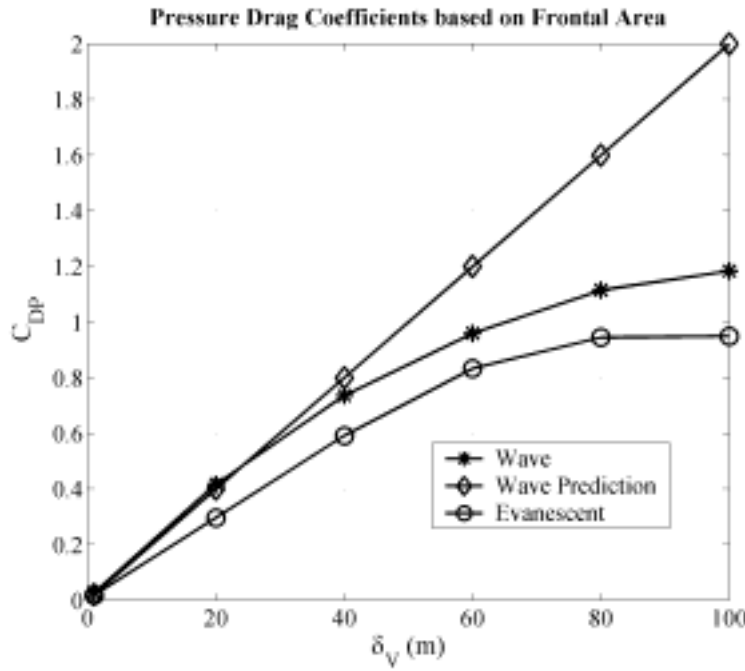

Figure 2. Mean drag coefficients for all the ridge numerical simulations, plotted versus vertical ridge height. Experiments in the wave-generating regime are plotted as stars, while those in the slow flow regime are plotted with circles. Our analytical prediction of the drag coefficient is plotted with diamonds. Ridges in both regimes can have large drag coefficients, leveling off to about 1 as the ridge size increases. The wave generating case matches the prediction well for small ridges.

The idealized modeling made it clear that vortex generation from sloping ridges could be an important process, both as the expression of pressure drag, and as a coherent flow structure in itself. However, vortex dynamics near complex bathymetry have been little-studied. From our 3-D numerical simulations of tidal flow at Three Tree Point (Fig. 3), we found that a vortical eddy was formed during each flood or ebb tide. The eddy extended through the full 200 m water depth, and its core followed the ridge crest slope (slope = 1:5, vertical:horizontal).

The snapshot in Fig. 3 is taken at the end of flood tide, where the flood direction is toward the lower right. The main feature is a large red volume of positive vorticity, which was created by flow separation from the Point during this flood tide. The current reverses early at the Point, and this is evident in blue (negative) vorticity on the slope behind the red volume. At the right edge of the red volume is a small blue volume, which is the remnant of the vortex created during the preceding ebb tide. It has been carried back to the south (lower right direction) by the flood tide. Vorticity of this strength takes 11 hours to complete a full circle.

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3 Tree Point, End of Flood, Vorticity (s^{-1})(Red: 3e-4, Blue: -3e-4)

Flood Current

Three Tree Point
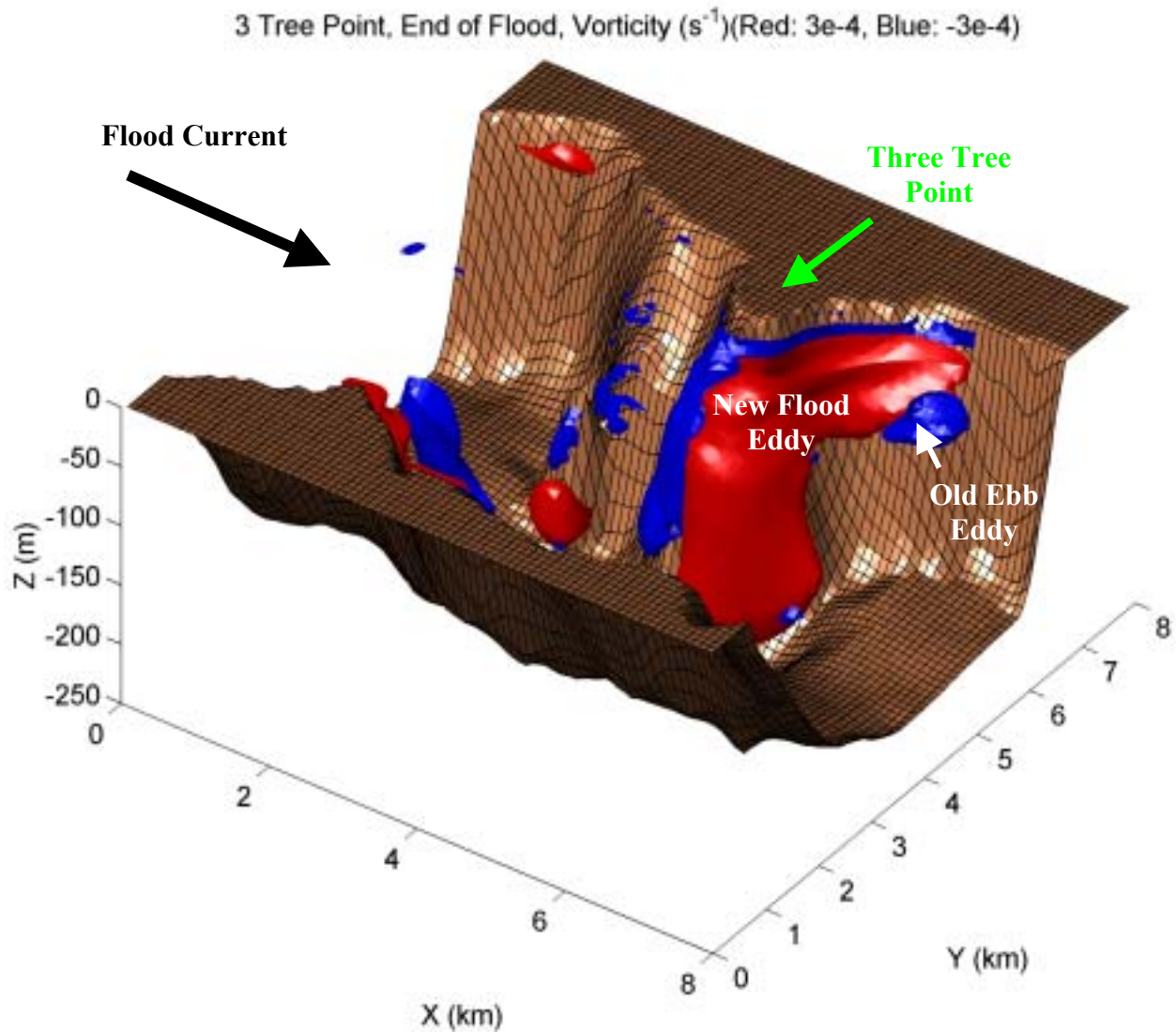
New Flood Eddy

Old Ebb Eddy

Figure 3. Volume visualization of vorticity in a numerical simulation of stratified, tidal flow at Three Tree Point in the Main Basin of Puget Sound, WA. Inside the red volume is water with relative vorticity > $3x10^{-4}$ s^{-1}. Inside the blue volume is water with relative vorticity < $-3x10^{-4}$ s^{-1}.

It is apparent that the vorticity signature of the eddy (especially the new red eddy) extends throughout the water column, and is fairly distorted by horizontal flows near the surface. In addition the eddy from the previous ebb (the small blue blob) shows that the eddy vorticity only survives at this level near the surface, and is apparently destroyed in some way deeper down.

Analysis of vorticity from drifter releases (August 2001) at Three Tree Point gives the same basic result: the eddies decay over less than 18 hours. Whereas simple scaling of their spindown by bottom friction suggests that they would survive at least 46 hours. The numerical simulation suggests a reason for this apparent contradiction: the eddies may be strongly sheared by interaction with neighboring eddies, leading to their rapid dissipation.

IMPACT/APPLICATION

The most important future impact of this work will come through the development of a parameterization of sub-grid-scale pressure drag based upon the pressure drag coefficient presented in Fig. 2. We plan a series of numerical simulations in the final year of the grant to do this.

TRANSITIONS

Our analytical prediction for the transition from wave to eddy regimes, modified to include the effects of Earth's rotation, are being used by Eric Kunze and Jon Nash (UW) in their interpretation of data from the TWIST experiment.

RELATED PROJECTS

Sonya Legg (WHOI) is doing numerical modeling of the TWIST region. Her work focuses on internal wave generation on a corrugated slope due to barotropic cross-slope flow, whereas ours focuses on motions forced by along-slope flow. Jim Moum (OSU) made microstructure measurements at Three Tree Point in March 2001, and has proposed (NSF) to do further work there, coordinating with our 2002 cruises.

PUBLICATIONS

MacCready, P. and G. Pawlak (2001) Stratified Flow along a Rough Slope: Separation Drag and Wave Drag. *J. Phys. Oceanogr.*, **31**, 2824-2839

Pawlak, G. and P. MacCready (in press) Oscillatory flow across an irregular boundary. *J. Geophys. Res.*

MacCready, P. and W. R. Geyer (2001) Estuarine Salt Flux Through an Isohaline Surface. *J. Geophys. Res.*, **106**, 11629-11637.

MacCready, P., R. D. Hetland, and W. R. Geyer (submitted): Long-Term Isohaline Salt Balance in an Estuary. Submitted to *Continental Shelf Res.*